

AD-A203 070

DTIC FILE COPY

④

OFFICE OF NAVAL RESEARCH

Contract N00014-86-K-0043

TECHNICAL REPORT No. 89

Photochemistry at Corrugated Thin Metal Films: A Phenomenological Approach

by

P. T. Leung, Y. S. Kim and Thomas F. George

Prepared for Publication

in

Photochemistry in Thin Films

Edited by Thomas F. George

Proceedings of the Society of Photo-Optical Instrumentation Engineers

Volume 1056

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

December 1988

Reproduction in whole or in part is permitted for any purpose of the
United States Government.

This document has been approved for public release and sale;
its distribution is unlimited.

DTIC
ELECTE
DEC 16 1988
S E D

28 10

58

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UBUFFALO/DC/88/TR-89			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Depts. Chemistry & Physics State University of New York		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) Fronczak Hall, Amherst Campus Buffalo, New York 14260			7b. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0043		
8c. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217			10. SOURCE OF FUNDING NUMBERS		
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) Photochemistry at Corrugated Thin Metal Films: A Phenomenological Approach					
12. PERSONAL AUTHOR(S) P. T. Leung, Y. S. Kim and Thomas F. George					
13a. TYPE OF REPORT		13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) December 1988		15. PAGE COUNT 9
16. SUPPLEMENTARY NOTATION Prepared for publication in Photochemistry in Thin Films, Edited by Thomas F. George, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Volume 1056					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	PHOTOCHEMISTRY, SELECTIVE PHOTOABSORPTION, THIN METAL FILMS, MOLECULAR DIPOLE, CORRUGATED SURFACE PLASMON. (JES)		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A phenomenological model is adopted to explore possible novel photochemical phenomena for molecules in the vicinity of a corrugated thin metal film, with detailed results worked out for the photoabsorption cross section for molecules in the vicinity of a grating film. A mechanism is proposed by which enhanced selective photoabsorption may be achieved based on the different nature of the coupling of the molecular dipole and the incident laser light to the surface plasmon modes of the thin films.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. David L. Nelson			22b. TELEPHONE (Include Area Code) (202) 696-4410		22c. OFFICE SYMBOL

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Photochemistry in Thin Films

Edited by Thomas F. George

Proceedings of the Society of Photo-Optical Instrumentation Engineers

Volume 1056 (1989)

Photochemistry at corrugated thin metal films: a phenomenological approach

P. T. Leung

Department of Physics, Portland State University
P. O. Box 751, Portland, Oregon 97201

Young Sik Kim* and Thomas F. George

Departments of Chemistry and Physics & Astronomy
239 Fronczak Hall, State University of New York at Buffalo
Buffalo, New York 14260

ABSTRACT

A phenomenological model is adopted to explore possible novel photochemical phenomena for molecules in the vicinity of a corrugated thin metal film, with detailed results worked out for the photoabsorption cross section for molecules in the vicinity of a grating film. A mechanism is proposed by which enhanced selective photoabsorption may be achieved based on the different nature of the coupling of the molecular dipole and the incident laser light to the surface plasmon modes of the thin films.

1. INTRODUCTION

The discovery of the dramatic surface-enhanced Raman scattering¹ has opened up the possibility of enhancing other photochemical processes by similar mechanisms employing the resonance condition of the surface plasmon field. Upon realizing the importance of surface roughness in these processes, intensive theoretical^{2,3} and experimental^{4,5} efforts have been devoted to the study of processes like photoabsorption/dissociation (direct dissociation) of molecules in the presence of both localized² and extended³ surface structures. By now, it has become clear that for such first-order processes, the surface-enhanced field and the induced decay rate will play the role of two competing factors in determining the ultimate enhancement of the process.²⁻⁴

In this work, we would like to explore the possibility of novel photochemical phenomena for molecules located in the vicinity of a thin metal film. Roughly speaking, when the thickness is thin enough, a thin-film system can be viewed as two surfaces interferring with each other, and hence we would expect richer proximity effects to arise. In the following, we shall study photoabsorption for these molecules by generalizing two of our previous works on photoabsorption³ and decay rates⁶ for the case of a single roughened surface.

* Present address: Department of Chemistry, Princeton University
Princeton, New Jersey 08544

2. PHOTOABSORPTION CROSS SECTION

The configuration of our problem is depicted in Fig. 1, where we consider a two-level system (modeled by a dipole moment $\vec{\mu}$) located at $z = d$ above a thin

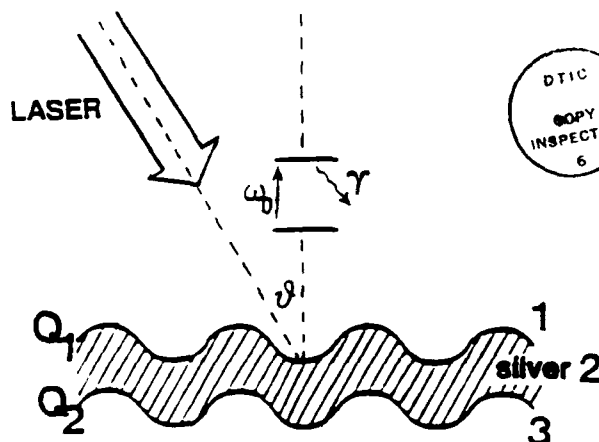


Figure 1. Configuration of the photoabsorption problem at a corrugated thin film.

metal (taken as Ag) film bounded by two grating surfaces located at $z = 0$ and $z = t$, respectively. Thus the profile functions take the simple forms

$$\zeta_1 = \zeta_{o1} e^{iQ_1 x}, \quad \zeta_2 = \zeta_{o2} e^{iQ_2 x}, \quad (1)$$

respectively, where we shall assume small corrugations ($\zeta_{oi} Q_i \ll 1$), so that perturbation theory can be applied. For simplicity, we consider only replicated films for which $\zeta_{o1} = \zeta_{o2} = \zeta_o$ and $Q_1 = Q_2 = Q_0$, although different combinations of ζ_1 and ζ_2 can also yield film systems of great interest.⁷ The optical properties of the three media are described by their dielectric functions ϵ_1 , $\epsilon_2 = \epsilon'(\omega) + i\epsilon''(\omega)$ and ϵ_3 , respectively. Consider p-polarized laser light of the form

$$\begin{aligned} \vec{E}_{in} &= (E_{ox} \hat{e}_x + E_{oz} \hat{e}_z) e^{i(k_z^{(0)} z - \omega t)} e^{i\vec{k}_{\parallel}^{(0)} \cdot \vec{r}_{\parallel}} \\ &= \vec{E}_o(\omega|z) e^{i\vec{k}_{\parallel}^{(0)} \cdot \vec{r}_{\parallel}}, \end{aligned} \quad (2)$$

$$\vec{k}_{\parallel}^{(0)} = k_x^{(0)} \hat{e}_x, \quad \vec{r}_{\parallel} = (x, y), \quad (3)$$

DTIC
COPY
INSPECTED
6

Accession For

NTIS GRA&I

DTIC TAB

Unannounced

Justification

By

Distribution/

Availability Codes

Dist

Avail and/or
Special

A-1

being incident on the system at an angle θ with the normal direction. We want to calculate the absorption cross section of the molecule. For simplicity, let us assume that the dipole $\vec{\mu}$ is oriented perpendicular ($\vec{\mu} = \mu \hat{e}_z$) to the film.

According to the phenomenological model,^{2,3} the absorption cross section for the free-molecule case can be obtained in a Lorentzian form as

$$\sigma_o(\omega) = A |\vec{E}_{in}|^2 \sin^2 \theta \frac{\gamma_M^o}{(\omega - \omega_M^o)^2 + (\gamma_M^o/2)^2}, \quad (4)$$

where A is a proportionality constant, and ω_M^o and γ_M^o denote the natural frequency and the width of the excited state for the free molecule, respectively. In the presence of the substrate film, Eq. (4) then becomes

$$\sigma(\omega) = A |E_z^{dr}(d, \omega)|^2 \frac{\gamma_M}{(\omega - \omega_M)^2 + (\gamma_M/2)^2}, \quad (5)$$

where $E_z^{dr}(d, \omega)$ is now the total field driving the dipole, and ω_M and γ_M denote the dressed values for the frequency and width, respectively, due to the presence of the film substrate. Since these are usually dependent on the driving frequency ω , Eq. (3) is in general distorted from a Lorentzian shape. Moreover, it is known that the induced frequency shift can most of the time be neglected compared to the induced decay rate,⁸ and hence in the following we shall assume $\omega_M \approx \omega_M^o$ and take into account only the substrate-induced decay rate which can be obtained as

$$\frac{\gamma_M}{\gamma_M^o} = 1 + \frac{3q\epsilon_1}{2k_1^3} \text{Im}G(\omega), \quad (6)$$

where

$$G(\omega) = \frac{E^r(d, \omega)}{\mu}, \quad (7)$$

q is the quantum yield of the emitting state, k_1 ($= \frac{\sqrt{\epsilon_1} \omega}{c}$) is the emission wave number, and $E^r(d, \omega)$ is the reflected field from the film upon incidence by the dipole emissions, acting back on the dipole. Our remaining job then is to calculate the fields E^{dr} and E^r .

3. SURFACE ELECTROMAGNETIC FIELDS

In order to calculate the surface fields generated by the incident laser field (E^{dr}) in Eq. (5) and the dynamic reflected field at the dipole site in Eq. (7), we resort to a perturbative approach formulated by Maradudin and Mills.⁹ According to their theory, the μ -th theory component for the roughness contribution (E^{Ro}) to the reflected field from first-order perturbation theory can be obtained as

$$E_{\mu}^{Ro}(\vec{r};\omega) = -\frac{k^2}{16\pi^3} \int d^2k_{\parallel} e^{i\vec{k}_{\parallel} \cdot \vec{r}_{\parallel}} \int dz' d_{\mu\nu}(\vec{k}_{\parallel}|\omega|zz) \{ [\epsilon_2 \theta(z'+t) - \epsilon_1] \delta(z') \\ \times \{ \xi(\vec{k}_{\parallel} - \vec{k}_{\parallel}^{(0)}) + [\epsilon_3 - \epsilon_2 \theta(-z')] \delta(z'+t) \} \{ \xi(\vec{k}_{\parallel} - \vec{k}_{\parallel}^{(0)}) + t \} \} \\ \times E_{\nu}^{(0)}(\vec{k}_{\parallel}^{(0)}|\omega|z') , \quad (8)$$

where \parallel denotes any vector on the xy-plane, ξ is the Fourier transform of the profile function, θ is the Heaviside step function, and $d_{\mu\nu}$ is the Fourier transform of the two-dimensional "flat propagator" obtained in Ref. 9. $E_{\nu}^{(0)}$ in Eq. (8) denotes the total field for the homogeneous case of a perfectly flat film. Hence, to calculate E^{dr} , one simply employs the expressions of $E_{\nu}^{(0)}$ for a flat film which are available in the literature.¹⁰ Similarly, for the calculation of E^r , the problem of $E_{\nu}^{(0)}$ has also been solved by Chance, Prock and Silbey in terms of the Green dyadics.⁸ Furthermore, we remark that to evaluate the integral of $\delta(z')$ in Eq. (8), where $E_{\nu}^{(0)}$ may be discontinuous across the boundaries of the film, one must adopt Agarwal's modifications and not just take the mean value of the integrals at each side of the boundary.^{6,11} Using the various appropriate $E^{(0)}$'s, we finally obtain¹²

$$E_z^{dr}(d,\omega) = (1 + R e^{2ik_1 d}) E_{in} \sin\theta + E_z^{Ro}(d,\omega) e^{ik_1 d} , \quad (9)$$

where R is the Fresnel reflectance for a flat film,¹⁰ and E_z^{Ro} is given by

$$E_z^{Ro}(d,\omega) = -\frac{k^2}{4\pi} \zeta_0 \{ (\epsilon_2 - \epsilon_1) [C_1 C_2 E_x^{(0)}(\omega|0_+) + C_4 E_z^{(0)}(\omega|0_+)] \\ + (\epsilon_3 - \epsilon_2) [C_1 C_3 E_x^{(0)}(\omega|-t_-) + C_5 E_z^{(0)}(\omega|-t_-)] \} e^{i\alpha_1 d} , \quad (10)$$

where $k = \omega/c$ and $E_x^{(0)}$, $E_z^{(0)}$ and α_1 are given in detail in Ref. 12. Similarly, we have⁷

$$E^r(d, \omega) = \frac{i\mu}{\epsilon_1} \int_0^\infty d\lambda \frac{\lambda^3}{h_1} (f_1 - 1) e^{2ih_1 d} + E_z^{Ro'}(d, \omega) \quad , \quad (11)$$

where

$$E_z^{Ro'}(d; \omega) = - \frac{k^2}{4\pi} \zeta_0 [(\epsilon_2 - \epsilon_1) I_1 + (\epsilon_3 - \epsilon_2) I_2] \quad , \quad (12)$$

with the functions f_1 and h_1 given in Ref. 7. In Eqs. (10) and (12), the coefficients C_i and the integrals I_i are complicated functions of the film parameters and are given in detail in Refs. 12 and 7. Hence, from Eqs. (6), (7), (11) and (12), we then obtain the complete determination of γ_M in terms of γ_M^0 . Taking this value for γ_M and together with Eq. (9) into Eq. (5), we can then calculate the photoabsorption cross section at the grating film $[\sigma(\omega)]$ for a given free-molecule cross section $\sigma_0(\omega)$.

4. POSSIBILITY OF ENHANCED SELECTIVE PHOTOABSORPTION

Instead of showing some straightforward model calculation based on Eqs. (4) and (5), here we shall pay attention to a very interesting feature of the problem which may lead to the realization of a mechanism for enhanced selective photoabsorption for adsorbed molecules. In a recent study,⁷ we have pointed out that the coupling of the molecular fluorescence radiation to the two thin-film surface plasmons is governed by very different dispersion relations as compared to those in the case of plane-wave light-scattering experiments. The difference arises from the dipole nature of the molecular emission which consists of a superposition of all the plane-wave harmonics. Hence the resonance peaks due to the cross-coupling of the plasmons on the two film surfaces into the long-(and short-)range surface plasmons [L(S)RSP] in the decay-rate spectrum are in general at different positions as compared to those in the light scattering spectrum.¹² Since these peak positions (in both spectra) are very sensitive to the geometrical (roughness, thickness,...) and dielectric properties of the film, for a given level ω_M^0 one can then try to adjust these parameters so that the cross-coupling peak of the scattered field lies close to ω_M^0 and that of the induced decay rate stays away from ω_M^0 . Upon optimal conditions, enhanced selective photoabsorption of this particular level (ω_M^0) may be achieved since the other levels close to it may now be damped seriously due to the fact that they can possibly experience large values for the induced decay rates.

As a numerical illustration, we consider a hypothetical molecular system with

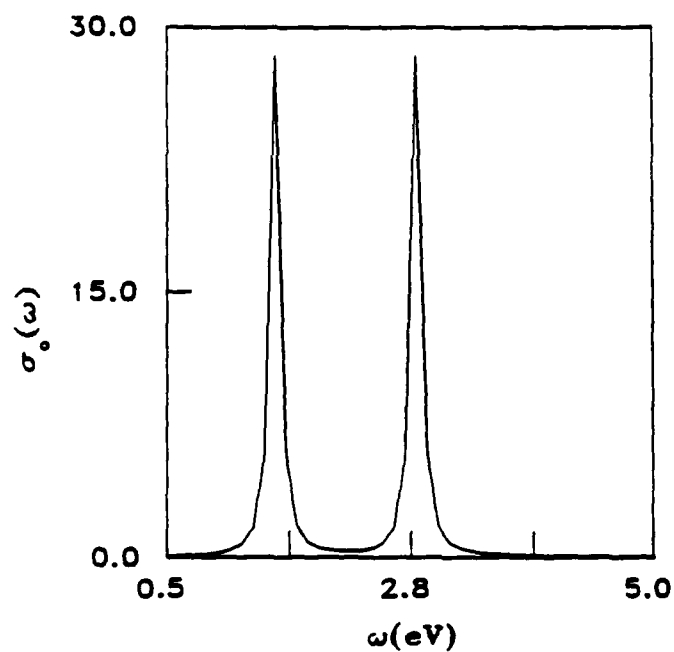


Figure 2. Hypothetical molecular system with two Lorentzian absorption lines.

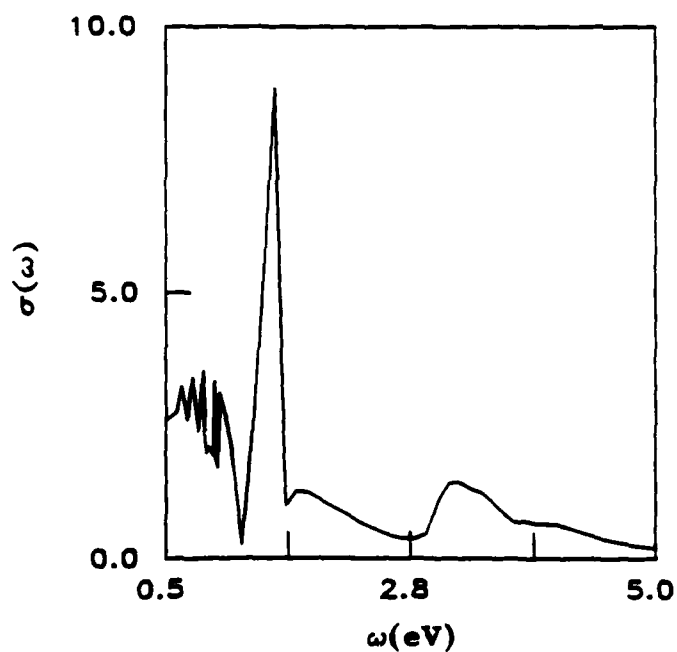


Figure 3. Distorted photoabsorption cross section for the molecular system in Fig. 2 in the presence of a Ag grating film, whose parameters are described in the text.

two Lorentzian absorption lines ω_M^0 as shown in Fig. 2. Let this system be located at $d = 150 \text{ \AA}$ from a supported grating film with $\epsilon_1 = 1.0$, $\epsilon_3 = 3.6$, $t = 100 \text{ \AA}$ and $Q = 1.5 \times 10^{-3}$. From previous analyses,^{7,12} the peak due to cross-coupling into LRSP is located at $\omega \sim 1.1 \text{ eV}$, whereas that for the light-scattering spectrum is at $\omega \sim 1.6 \text{ eV}$. Note that at this distance the coupled SRSP almost vanishes and does not play a role in the photabsorption process. Hence for the system as shown in Fig. 2, we expect that only the one with $\omega_M^0 \sim 1.5 \text{ eV}$ will be excited and the other one will be suppressed due to the surface-induced damping. Indeed, these effects are manifested in Fig. 3 where we show a plot of $\sigma(\omega)$, except that no enhancement of the line at 1.5 eV is observed, due to the fact that the corrugation amplitude used in this calculation ($\zeta_0 \sim 40 \text{ \AA}$) is not large enough. We have tried to increase this to go beyond 100 \AA , where we do see enhancement, but then the result goes beyond the validity of our present perturbative approach. Nevertheless, the present results do give very strong indications that such enhanced selective photoabsorption may indeed be possible for deeper grating films, where a non-perturbative treatment must be used.

5. CONCLUSION

It is well known that due to its monochromaticity and tunability, the laser has found great applications in various selective photochemical processes. Nevertheless, to have the selective absorption enhanced, one requires a highly-intense laser source, which may then lead to multiphoton processes and hence weakens the selectivity in the photoprocess. In this present mechanism that we are proposing, however, we have made use of the fact that the induced decay rate and the enhanced LRSP field have very different resonance structures, and hence excitation of other levels may be suppressed by the enhanced decay rates at their natural frequencies. Hence, we conclude that it is worth pursuing the problem further using a non-perturbative approach to allow large grating amplitudes for the film and to recalculate $\sigma(\omega)$ for such a system, so that a realistic enhanced selective photoabsorption may be exhibited.

6. ACKNOWLEDGMENTS

This research was supported by the Office of Naval Research, the National Science Foundation under Grant CHE-8620274 and the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

7. REFERENCES

1. M. Fleischmann, P. J. Handra and A. J. McQuillan, Chem. Phys. Lett. 26, 163 (1974).
2. J. I. Gersten and A. Nitzan, Surf. Sci. 158, 165 (1985), and references therein.
3. P. T. Leung and T. F. George, J. Chem. Phys. 85, 4729 (1986).
4. G. M. Goncher, C. A. Parsons and C. B. Harris, J. Phys. Chem. 88, 4200 (1984).
5. R. A. Wolkow and M. Moskovits, J. Chem. Phys. 87, 5858 (1987).
6. P. T. Leung and T. F. George, Phys. Rev. B 36, 4664 (1987).
7. P. T. Leung, Y. S. Kim and T. F. George, Phys. Rev. B, submitted.
8. R. R. Chance, A. Prock and R. Silbey, Adv. Chem. Phys. 37, 1 (1978).
9. A. A. Maradudin and D. L. Mills, Phys. Rev. B 11, 1392 (1975); D. L. Mills and A. A. Maradudin, Phys. Rev. B 12, 2943 ((

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	<u>No. Copies</u>		<u>No. Copies</u>
Office of Naval Research Attn: Code 1113 800 N. Quincy Street Arlington, Virginia 22217-5000	2	Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Dr. Bernard Douda Naval Weapons Support Center Code 50C Crane, Indiana 47522-5050	1	Naval Weapons Center Attn: Dr. Ron Atkins Chemistry Division China Lake, California 93555	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko, Code L52 Port Hueneme, California 93401	1	Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12 high quality	U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
DTNSRDC Attn: Dr. H. Singerman Applied Chemistry Division Annapolis, Maryland 21401	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375-5000	1	Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 92132	1
		Dr. David L. Nelson Chemistry Division Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217	1

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. J. E. Jensen
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. J. H. Weaver
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minnesota 55455

Dr. A. Reisman
Microelectronics Center of North Carolina
Research Triangle Park, North Carolina
27709

Dr. M. Grunze
Laboratory for Surface Science and
Technology
University of Maine
Orono, Maine 04469

Dr. J. Butler
Naval Research Laboratory
Code 6115
Washington D.C. 20375-5000

Dr. L. Interante
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Irvin Heard
Chemistry and Physics Department
Lincoln University
Lincoln University, Pennsylvania 19352

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506

Dr. C. B. Harris
Department of Chemistry
University of California
Berkeley, California 94720

Dr. F. Kutzler
Department of Chemistry
Box 5055
Tennessee Technological University
Cookeville, Tennessee 38501

Dr. D. DiLella
Chemistry Department
George Washington University
Washington D.C. 20052

Dr. R. Reeves
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Steven M. George
Stanford University
Department of Chemistry
Stanford, CA 94305

Dr. Mark Johnson
Yale University
Department of Chemistry
New Haven, CT 06511-8118

Dr. W. Knauer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. G. A. Somorjai
Department of Chemistry
University of California
Berkeley, California 94720

Dr. J. Murday
Naval Research Laboratory
Code 6170
Washington, D.C. 20375-5000

Dr. J. B. Hudson
Materials Division
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Theodore E. Madey
Surface Chemistry Section
Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

Dr. J. E. Demuth
IBM Corporation
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. M. G. Lagally
Department of Metallurgical
and Mining Engineering
University of Wisconsin
Madison, Wisconsin 53706

Dr. R. P. Van Duyne
Chemistry Department
Northwestern University
Evanston, Illinois 60637

Dr. J. M. White
Department of Chemistry
University of Texas
Austin, Texas 78712

Dr. D. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940

Dr. R. L. Park
Director, Center of Materials
Research
University of Maryland
College Park, Maryland 20742

Dr. W. T. Peria
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Keith H. Johnson
Department of Metallurgy and
Materials Science
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. S. Sibener
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Arnold Green
Quantum Surface Dynamics Branch
Code 3817
Naval Weapons Center
China Lake, California 93555

Dr. A. Wold
Department of Chemistry
Brown University
Providence, Rhode Island 02912

Dr. S. L. Bernasek
Department of Chemistry
Princeton University
Princeton, New Jersey 08544

Dr. W. Kohn
Department of Physics
University of California, San Diego
La Jolla, California 92037

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Richard Colton
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Dan Pierce
National Bureau of Standards
Optical Physics Division
Washington, D.C. 20234

Dr. R. Stanley Williams
Department of Chemistry
University of California
Los Angeles, California 90024

Dr. R. P. Messmer
Materials Characterization Lab.
General Electric Company
Schenectady, New York 22217

Dr. Robert Gomer
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Ronald Lee
R301
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

Dr. Paul Schoen
Code 6190
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. John T. Yates
Department of Chemistry
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. L. Kesmodel
Department of Physics
Indiana University
Bloomington, Indiana 47403

Dr. K. C. Janda
University of Pittsburgh
Chemistry Building
Pittsburg, PA 15260

Dr. E. A. Irene
Department of Chemistry
University of North Carolina
Chapel Hill, North Carolina 27514

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974

Dr. Martin Fleischmann
Department of Chemistry
University of Southampton
Southampton SO9 5NH
UNITED KINGDOM

Dr. H. Tachikawa
Chemistry Department
Jackson State University
Jackson, Mississippi 39217

Dr. John W. Wilkins
Cornell University
Laboratory of Atomic and
Solid State Physics
Ithaca, New York 14853

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. R. G. Wallis
Department of Physics
University of California
Irvine, California 92664

Dr. D. Ramaker
Chemistry Department
George Washington University
Washington, D.C. 20052

Dr. J. C. Hemminger
Chemistry Department
University of California
Irvine, California 92717

Dr. T. F. George
Chemistry Department
University of Rochester
Rochester, New York 14627

Dr. G. Rubloff
IBM
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. Horia Metiu
Chemistry Department
University of California
Santa Barbara, California 93106

Dr. W. Goddard
Department of Chemistry and Chemical
Engineering
California Institute of Technology
Pasadena, California 91125

Dr. P. Hansma
Department of Physics
University of California
Santa Barbara, California 93106

Dr. J. Baldeschwieler
Department of Chemistry and
Chemical Engineering
California Institute of Technology
Pasadena, California 91125

Dr. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

Dr. R. W. Plummer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 44106

Dr. N. Winograd
Department of Chemistry
Pennsylvania State University
University Park, Pennsylvania 16802

Dr. Roald Hoffmann
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. A. Steckl
Department of Electrical and
Systems Engineering
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. G.H. Morrison
Department of Chemistry
Cornell University
Ithaca, New York 14853